

NASA TECHNICAL NOTE



NASA TN D-4819

01

NASA TN D-4819

LOAN COPY: F
AFWL (W
KIRTLAND AF.



LIQUID-VAPOR INTERFACE CONFIGURATIONS IN TOROIDAL TANKS DURING WEIGHTLESSNESS

by Eugene P. Symons and Kaleel L. Abdalla

*Lewis Research Center
Cleveland, Ohio*

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1968



ERRATA

NASA Technical Note D-4819

LIQUID-VAPOR INTERFACE CONFIGURATIONS IN
TOROIDAL TANKS DURING WEIGHTLESSNESS

By Eugene P. Symons and Kaleel L. Abdalla

October 1968

Page 13, figure 11: In the key, the value of θ for the left column of diagrams should be 0^0 and for the right column should be $0^0 < \theta \leq 90^0$.

Completed
18 Dec 68
54



LIQUID-VAPOR INTERFACE CONFIGURATIONS IN
TOROIDAL TANKS DURING WEIGHTLESSNESS

By Eugene P. Symons and Kaleel L. Abdalla

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 - CFSTI price \$3.00

ABSTRACT

An experimental investigation was conducted in the Lewis Research Center drop tower facility to study the isothermal liquid-vapor interface configuration in a toroidal tank during weightlessness for a 0° -static-contact-angle liquid. Results are presented for a range of liquid volumes in tanks normally positioned horizontally and also for tanks mounted at angles to the gravity field prior to the weightless test. The angle tests simulated the effect of nonaxial maneuvers on the initial position of the liquid-vapor interface before entering weightlessness. Three basic interface configurations were observed and were shown to be dependent on tank mounting angle and liquid volume and to be independent of tank size.

LIQUID-VAPOR INTERFACE CONFIGURATIONS IN TOROIDAL TANKS DURING WEIGHTLESSNESS

by Eugene P. Symons and Kaleel L. Abdalla

Lewis Research Center

SUMMARY

An experimental investigation was conducted in the Lewis Research Center 2.2-second drop tower facility to study the isothermal liquid-vapor interface configuration in a toroidal tank during weightlessness for a liquid with 0° static contact angle. Results are presented for a range of percentages of liquid volume in tanks which were normally positioned horizontally. In addition, results are given for tanks mounted at various angles to the gravity field prior to the weightless test. These angle tests simulated the effect that nonaxial maneuvers would have on the initial position of the liquid vapor interface before entering weightlessness. Three basic interface configurations were observed and were shown to be dependent on tank mounting angle and percentage of liquid volume and to be independent of tank size.

INTRODUCTION

The study of the liquid-vapor interface configuration in various tank geometries during weightlessness has been the basis of a broad experimental program conducted at the Lewis Research Center. This study has included an extensive investigation of configurations in cylinders and spheres (refs. 1 to 4) because of their direct applicability to present day vehicles. Recently, however, the toroidal tank has been suggested for use as a propellant tank because of its amenability to efficient vehicle packaging. One of the requirements for evaluation of toroidal tank systems is a knowledge of the configuration of the liquid-vapor interface so that such operations as the draining of liquid and the venting of excess tank pressure can be studied. To date, there are no known studies, either theoretical or experimental, of the configuration of the liquid-vapor interface in a toroid during weightlessness. Some sloshing data have been published (refs. 5 and 6). However, these data pertain only to normal gravity.

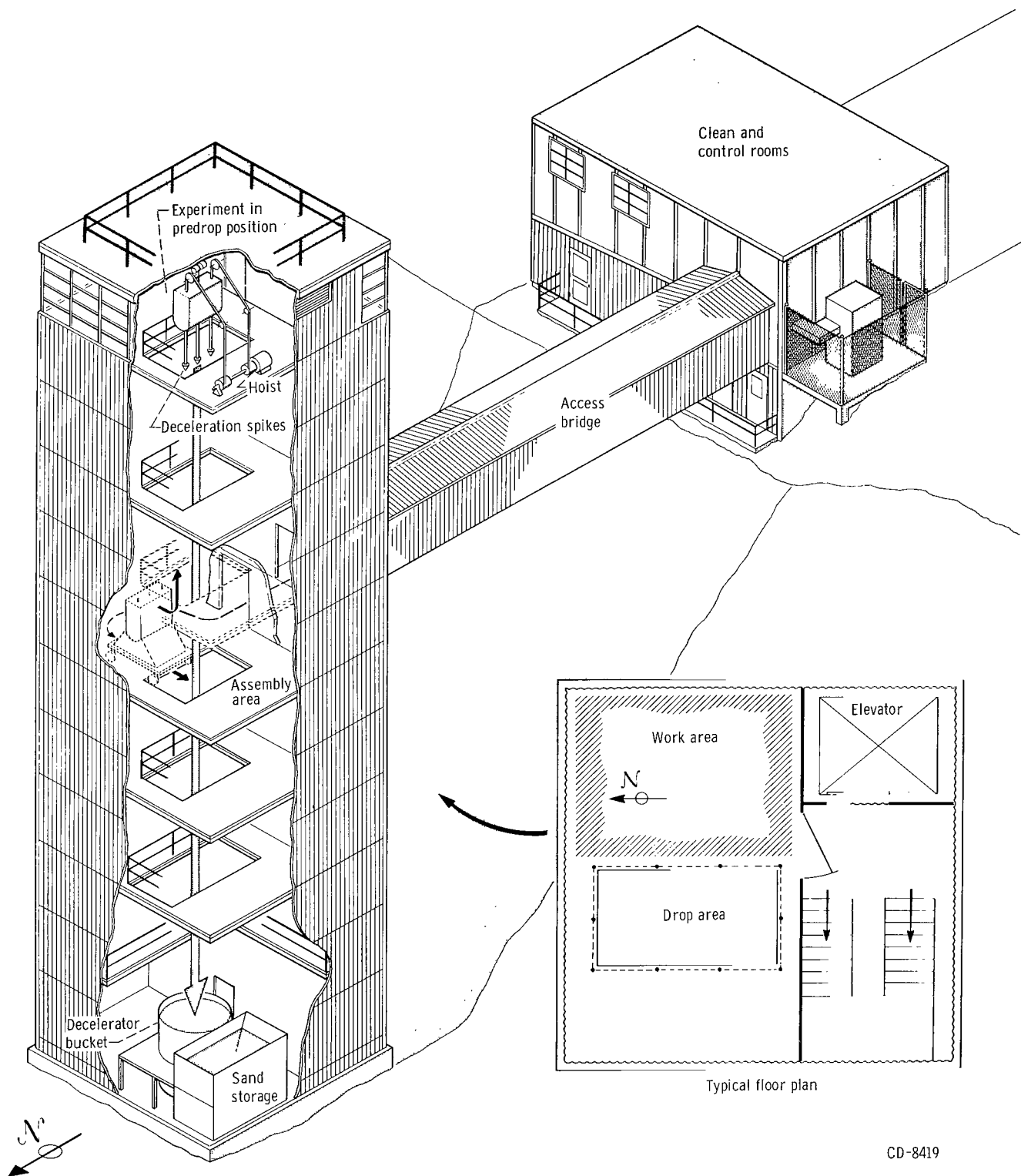


Figure 1. - Drop tower facility.

CD-8419

This report presents the results of an experimental investigation of the isothermal liquid-vapor interface configuration in toroid tanks during weightlessness. The liquids used in the tests had a 0° static contact angle. Results are presented for a range of percentages of liquid volume in tanks which were normally positioned horizontally. In addition, results are given for tanks mounted at various angles to the gravity field prior to the weightless test. These angle tests simulated the effect that nonaxial maneuvers would have on positioning the liquid-vapor interface away from its normal position in an actual tank prior to entering weightlessness. Results are presented in photographic and chart form.

APPARATUS AND PROCEDURE

Test Facility

The experimental investigation was conducted in the Lewis drop tower facility shown in figure 1. This facility provides 2.2 seconds of weightlessness by allowing the package to free fall a distance of 24 meters while enclosed in a protective drag shield. The drag shield has a high ratio of weight to frontal area and a low drag coefficient to maintain deceleration as a result of air drag on the experiment package below 10^{-5} g's. During the drop, the package and drag shield fall simultaneously but are independent of each other (see fig. 2). At the conclusion of the drop, the package is decelerated by impingement of

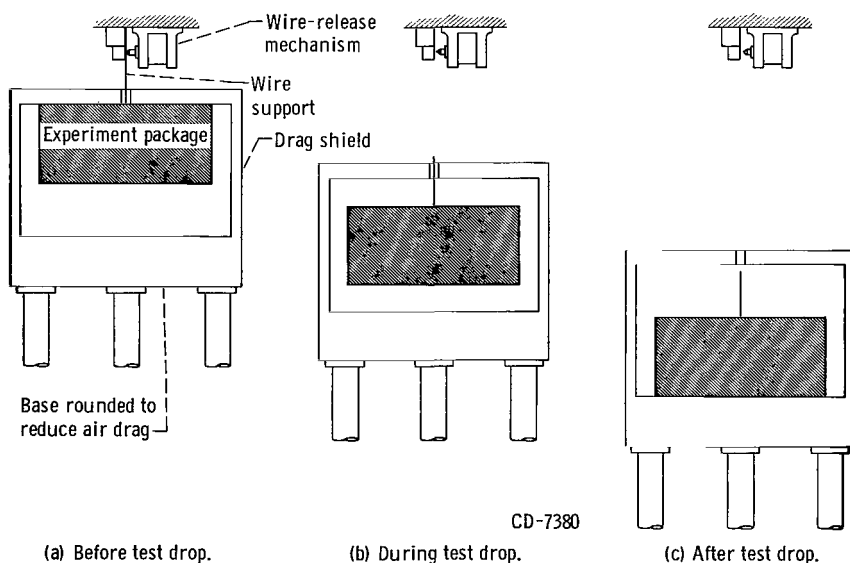
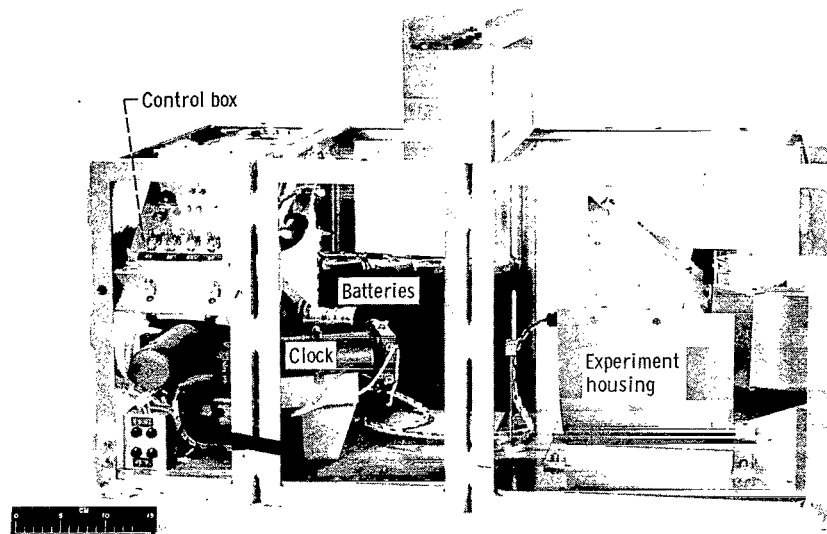
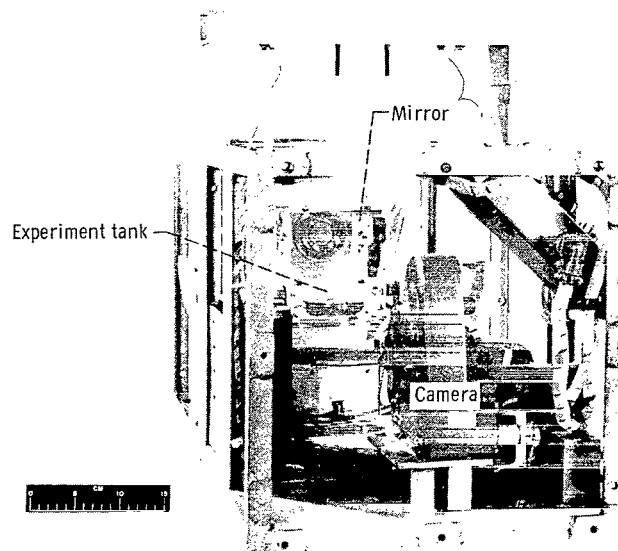


Figure 2. - Schematic drawing showing position of experiment package and drag shield before, during, and after test drop.



C-68-596

(a) Side view.



C-68-597

(b) End view.

Figure 3. - Experiment package.

the airdrag shield spikes in a bed of sand. A more complete description of the test facility can be found in reference 2.

Experiment Package

The experiment package shown in figure 3 is self-contained and consists of an experiment tank, a photographic and lighting system, a digital clock, and an electrical system to operate the various components. The test tank is indirectly illuminated by means of backlighting contained in the experiment housing (fig. 4) which provides sufficient light so that the movement of the liquid-vapor interface can be recorded with a 16-millimeter camera. A mirror, positioned at a 45° angle relative to the experiment tank gives a top view of the experiment. A digital clock with a calibrated accuracy of 0.01 second is also located in the field of view of the camera so that elapsed times during the weightless test may be recorded. All electrical components were operated automatically through a control box and received their power from rechargeable nickel cadmium batteries carried on board the experiment package.

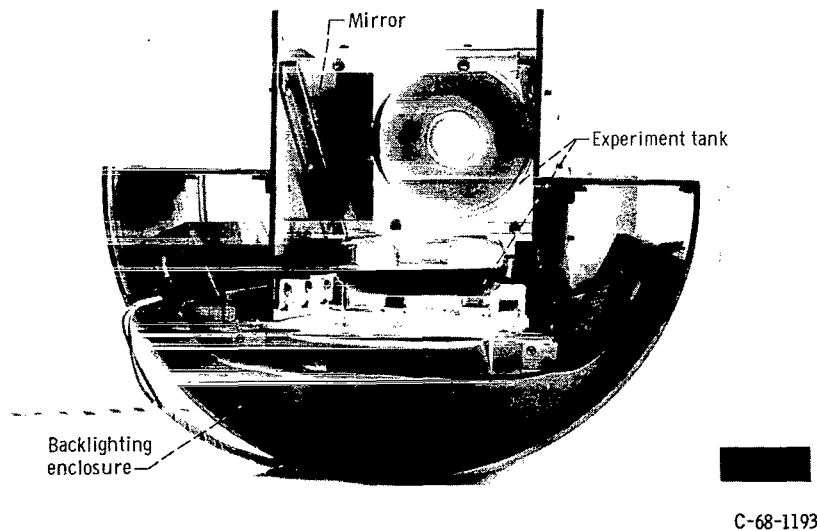


Figure 4. - Experiment housing containing backlighting enclosure.

Experiment Tanks and Test Liquid

The experiment tanks used in this investigation were toroids machined from cast acrylic plastic and polished for photographic purposes. Three tank sizes were tested with major radii R of 4, 3, and 2 centimeters and minor radii r of 2, 1, and 1 centimeters, respectively (see fig. 5). The maximum tank size was limited by the space available in the experiment package and the free-fall test time of 2.2 seconds.

The test liquid was anhydrous ethanol. This liquid was chosen because it exhibits an essentially 0° static contact angle with cast acrylic plastic and thus duplicates the static contact angle of most liquids on spacecraft tank materials. To improve photographic quality, a small amount of dye which had no measurable effect on the fluid properties was added to the test liquid.

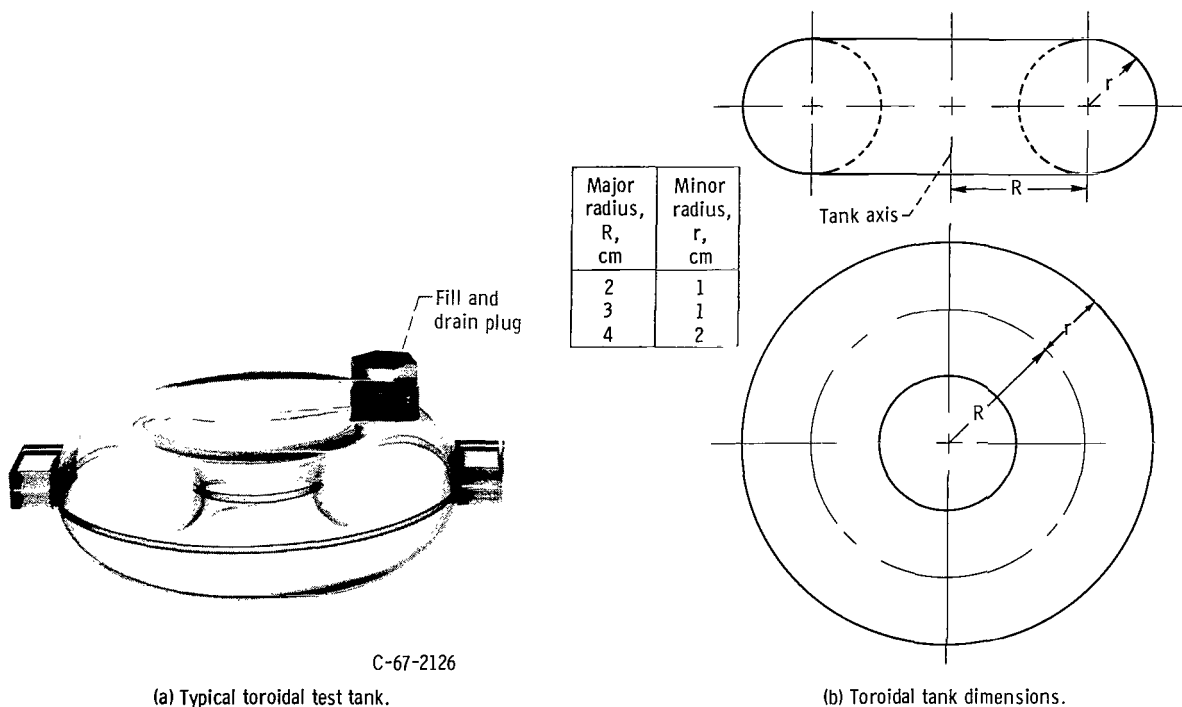


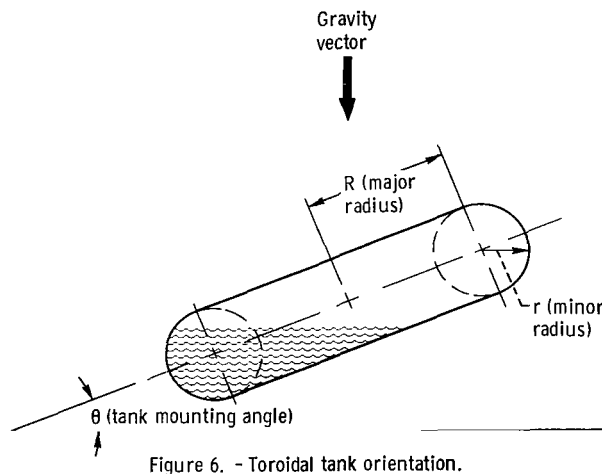
Figure 5. - Experiment tanks.

Test Procedure

The test procedure consisted of cleaning, filling, and mounting the tank in the experiment package, setting the desired tank mounting angle, and performing the weightless test.

The tank was first cleaned in an ultrasonic cleaner with a mild aqueous detergent solution so that the wetting characteristics of the test liquid would not be influenced by contaminants. The tank was then filled to the desired level with the test liquid and mounted in the backlighting housing (fig. 4).

The tank mounting angle (fig. 6) was then set by rotating the backlighting housing



about its semicircular base. Normally, the tank was positioned so that the tank mounting angle θ was 0° (tank horizontal); however, in order to determine the effect of initial conditions, the tank was also mounted at various angles. This effectively changed the initial condition of the liquid-vapor interface before entering weightlessness. After positioning the experiment tank with its housing at the approximate mounting angle, the package was then balanced about its horizontal axes. A combination level was then used to adjust the base so that the required tank mounting angle was precisely obtained.

The package was placed in the drag shield and hoisted to the predrop position where the entire assembly was suspended with a highly stressed music wire. A cutter, driven by compressed air, notched the wire causing it to fail, and the package entered free fall.

RESULTS AND DISCUSSION

Normal Initial Condition, $\theta = 0^\circ$

When the tank mounting angle was set at 0° , the liquid-vapor interface was initially positioned in a plane perpendicular to the tank axis. From this initial condition, the liquid-vapor interface formed three configurations during weightlessness dependent on the percentage of liquid volume. The results are summarized in the bar graph shown in figure 7 where each bar represents one tank geometry.

At liquid volumes as large as 50 percent, the liquid in each tank moved to a position on the tank wall farthest away from the tank axis, while the vapor occupied the wall nearest the tank axis (see key in fig. 7). This region is represented by the lower shaded portion of each bar. Typical liquid and vapor configurations in this region are shown in figure 8. Note that the liquid appears to be located uniformly along the "outer" wall and that the liquid-vapor interface is curved.

Above 50 percent volume, there existed a transition region (as noted in fig. 7) in which the behavior of the liquid and vapor was not so predictable. In this transition region, the interface did not reach a static equilibrium configuration during the weightless test period. Some motion was evident at the end of this test time and the final interface shape could only be estimated. A typical sequence illustrating the interface motion in the transition region is presented in figure 9. Initially, upon entering weightlessness, the

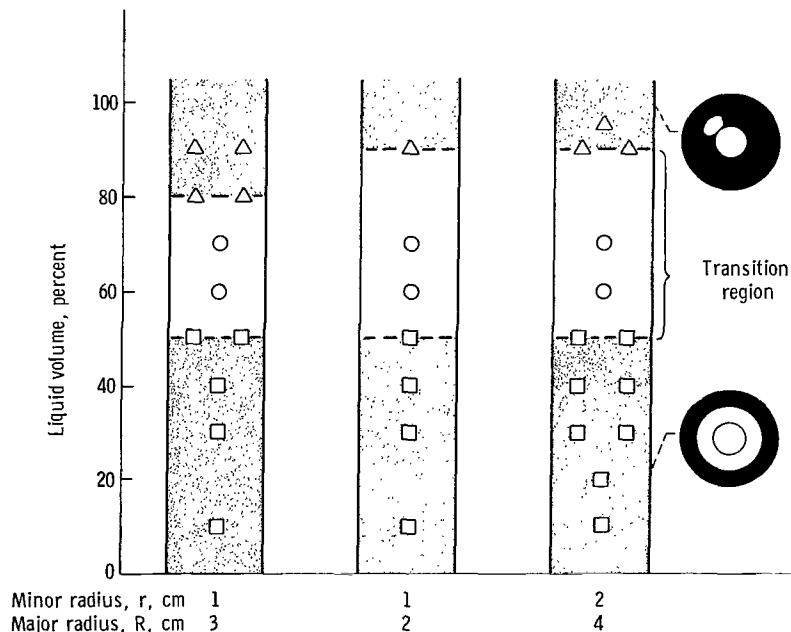
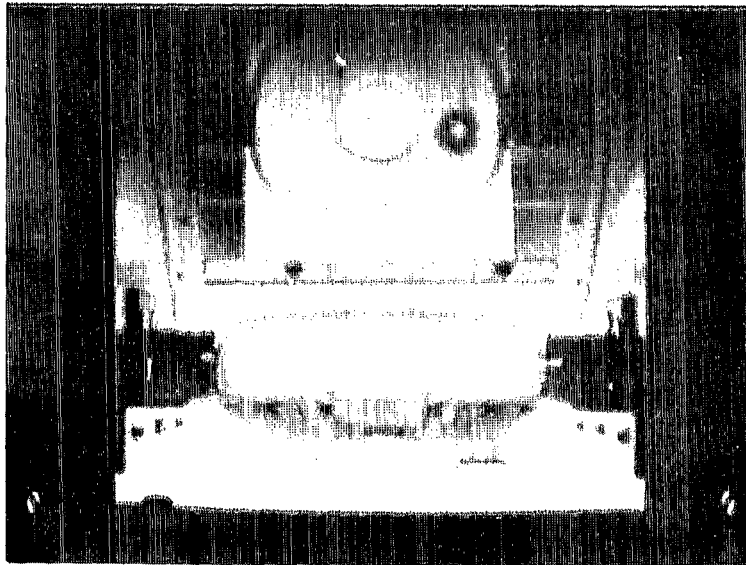
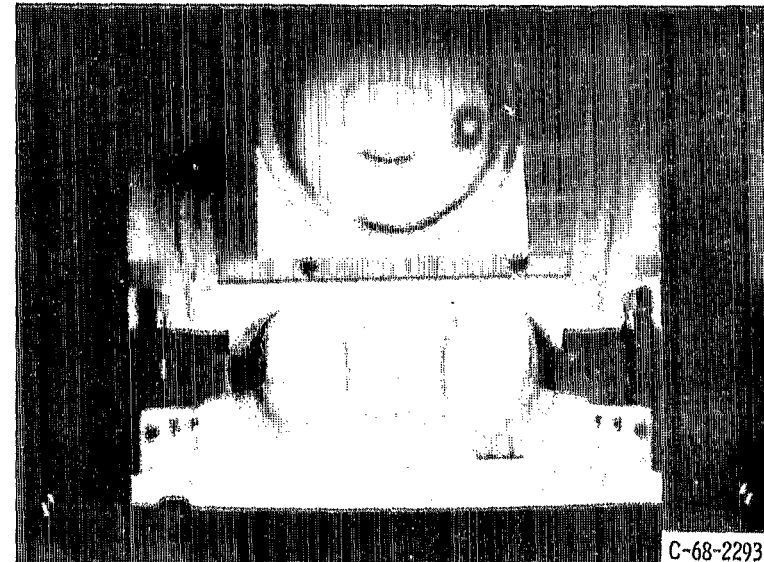


Figure 7. - Effect of percentage of liquid volume and tank geometry on liquid-vapor interface configuration during weightlessness. (Tank mounting angle, $\theta = 0^\circ$.)



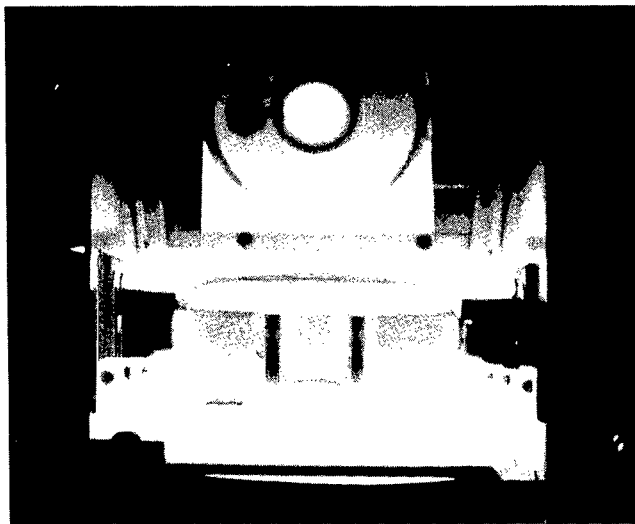
(a) Normal-gravity configuration.



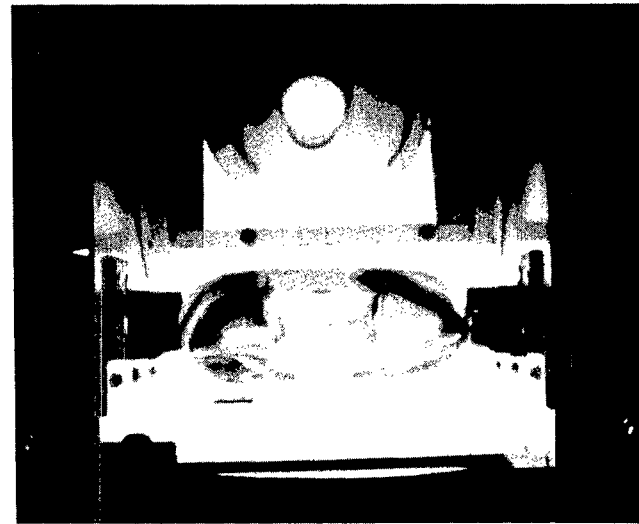
(b) Zero-gravity configuration.

C-68-2293

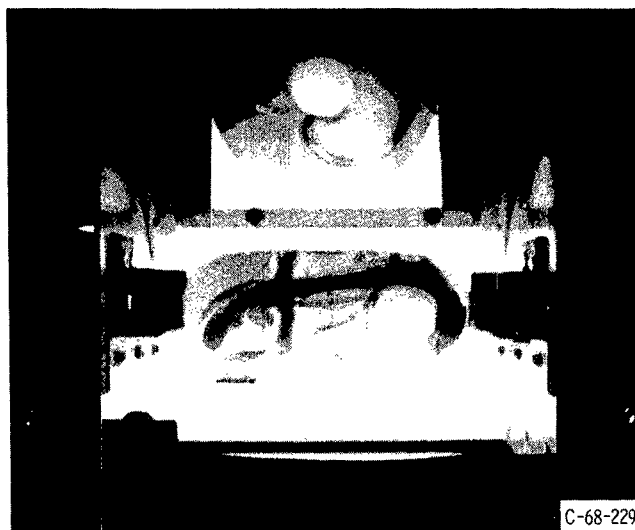
Figure 8. - Configuration of liquid-vapor interface during weightlessness for toroidal tank with low percentage of liquid volume (30 percent full) and 0° tank mounting angle. Major radius, 4 centimeters; minor radius, 2 centimeters.



(a) Normal-gravity configuration.



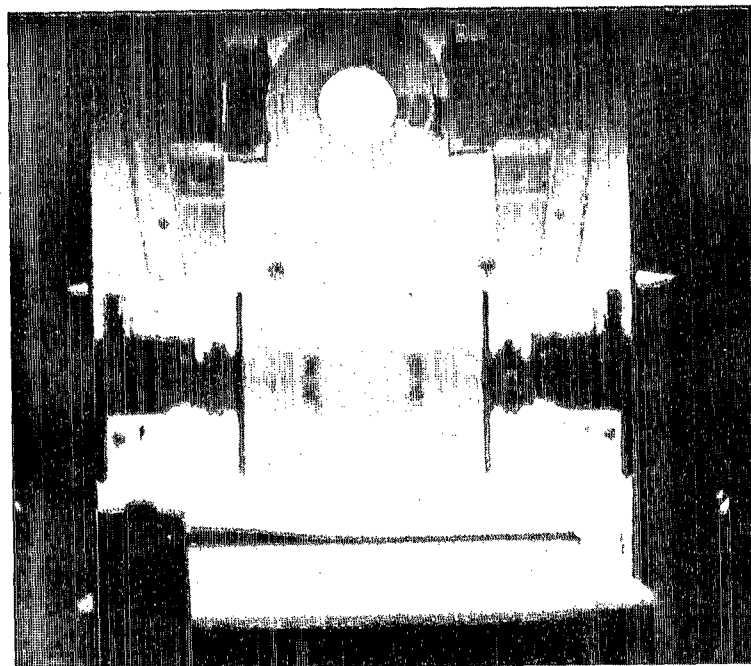
(b) Initiation of free fall.



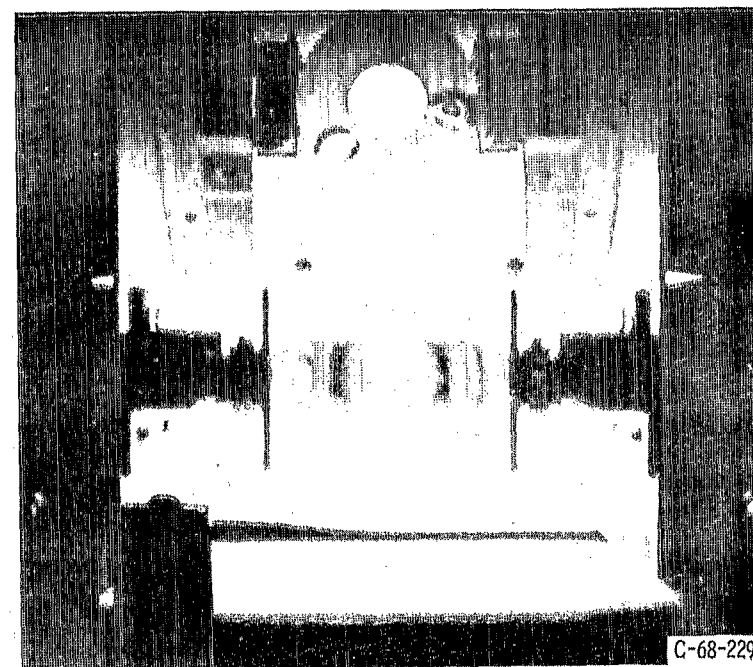
C-68-2294

(c) Necking down of bubble.

Figure 9. - Configuration of liquid-vapor interface during weightlessness for toroidal tank with moderate to high percentage of liquid volume (70 percent full) and 0° tank mounting angle. Transition region. Major radius, 4 centimeters; minor radius, 2 centimeters.



(a) Normal-gravity configuration.



(b) Zero-gravity configuration.

Figure 10. - Configuration of liquid-vapor interface during weightlessness for toroidal tank with high percentage of liquid volume (90 percent) and 0° tank mounting angle. Major radius, 3 centimeters; minor radius, 1 centimeter.

liquid began to move to the "outer" tank wall and the vapor to the "inner" tank wall (fig. 9(b)). However, as the package continued to free fall, the vapor bubble, which was very nearly toroidal in shape, "necked down" in one or more locations (fig. 9(c)). Although it was impossible to observe the final liquid-vapor interface configuration because the liquid interface was constantly in motion, the liquid seemed to be collecting about the location in which the vapor bubble had initially necked down with the remainder of the liquid positioned at the outer wall. It appeared that eventually the entire bulk of the liquid would have collected in this manner; however, it was impossible to achieve complete equilibrium even in the smallest test tank because of the limitation in the available test time. Note that, as shown in figure 7, the upper limit for the region in which this interface configuration occurs depends on the tank proportion. For example, for the experiment tank which had $R/r = 3$ (major radius, 3 cm and minor radius, 1 cm) the upper limit for this region was about 80 percent liquid volume, while for the two tanks with $R/r = 2$ (major radius, 4 cm and minor radius, 2 cm; major radius, 2 cm and minor radius, 1 cm) the upper limit was about 90 percent.

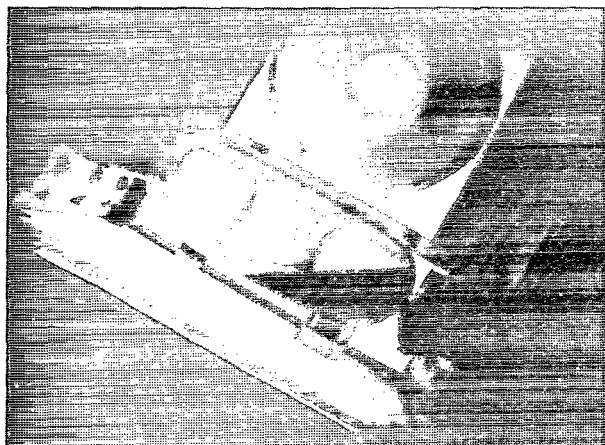
As the percentage of liquid volume was increased, the likelihood that the toroidal vapor bubble would neck down in more than one place correspondingly increased. Above the upper limit of the transition region, any necking down of the bubble resulted in the formation of one or more spherical bubbles, as shown in figure 10. (Three bubbles were the most observed in these tests.) This configuration would be expected at these high percentages of liquid volume since the volume of vapor could then form a spherical shape consistent with the theory that the liquid and vapor assume a configuration in which the surface energy of the system is at a minimum.

Initial Condition, $\theta > 0^\circ$

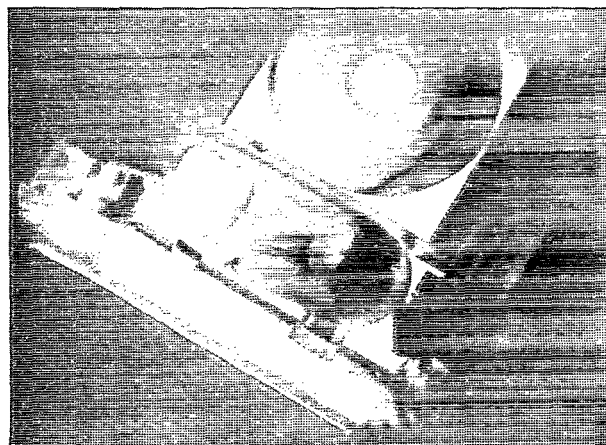
When the tank was initially positioned at some mounting angle greater than 0° , the liquid-vapor interface formed three distinct configurations during weightlessness. These configurations were dependent on the percentage of liquid volume and the tank mounting angle. The effect of each of these variables on the interface configuration is summarized in figure 11, which also includes the data obtained for a tank mounted at 0° .

Note that for low percentages of liquid volume (less than about 20 or 30 percent, depending on the tank proportion) the bulk of the liquid collects on the "outer" wall of the toroid in that section of the tank in which it was initially located. This region is represented by the lower shaded areas shown in figure 11. Typical configurations of the interface in this region are shown in figure 12. The liquid thickness on the outer wall appears to be larger in that section in which the initial normal-gravity depth was greatest. We believe that this configuration is analogous to that formed at liquid volumes of 50 percent

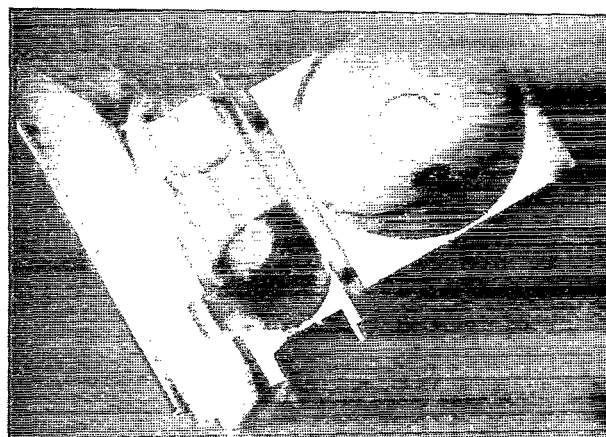
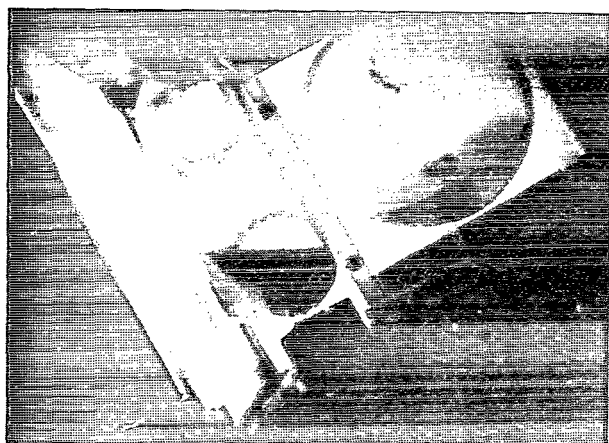
Normal-gravity configuration



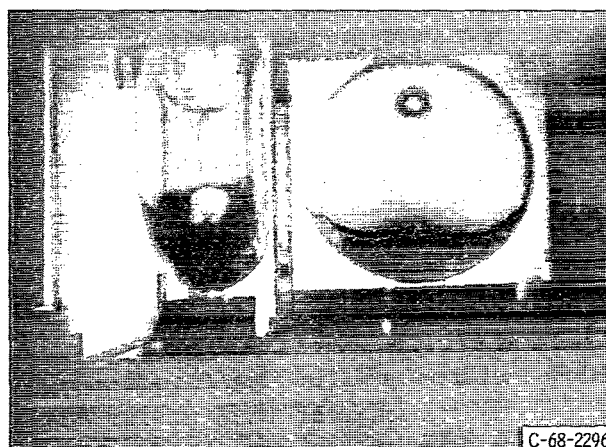
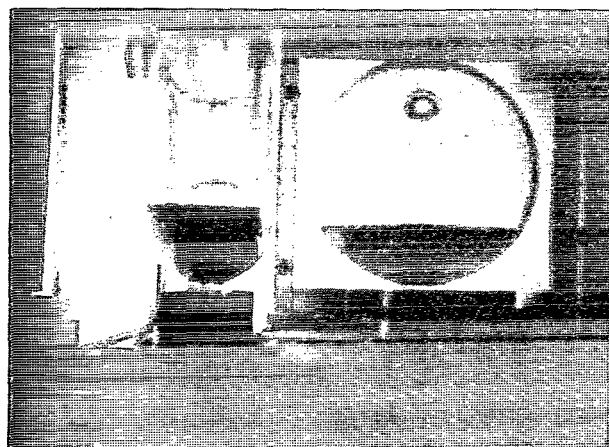
Zero-gravity configuration



(a) Tank mounting angle, 30° .



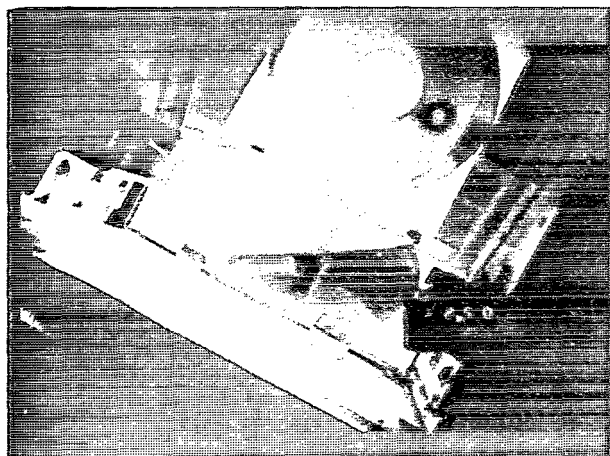
(b) Tank mounting angle, 60° .



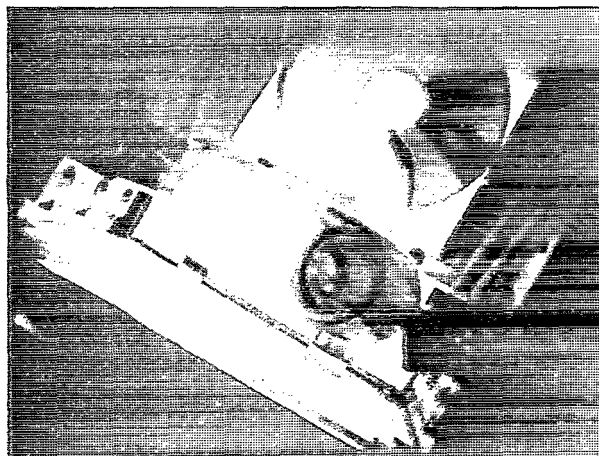
(c) Tank mounting angle, 90° .

Figure 12. - Configuration of liquid-vapor interface during weightlessness for low percentage of liquid volume (20 percent full) and tank mounting angle greater than 0° . Major radius, 4 centimeters; minor radius, 2 centimeters.

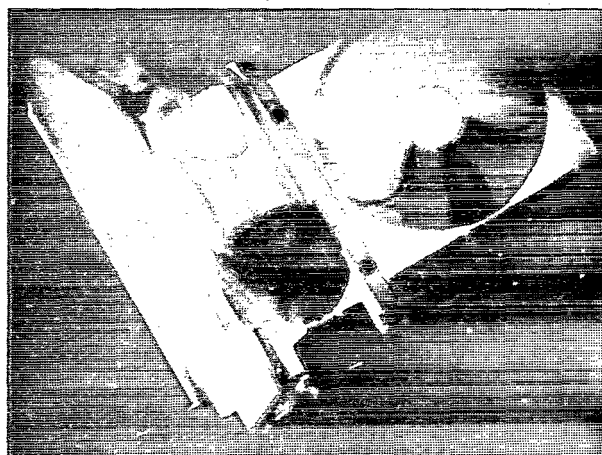
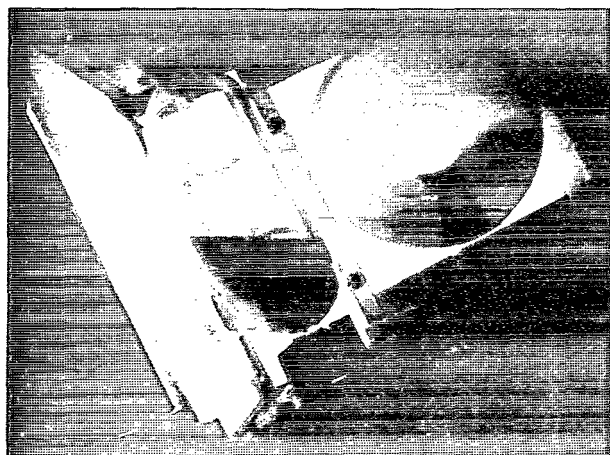
Normal-gravity configuration



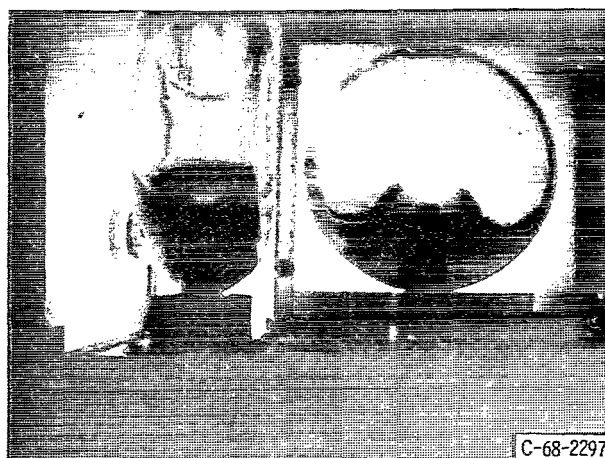
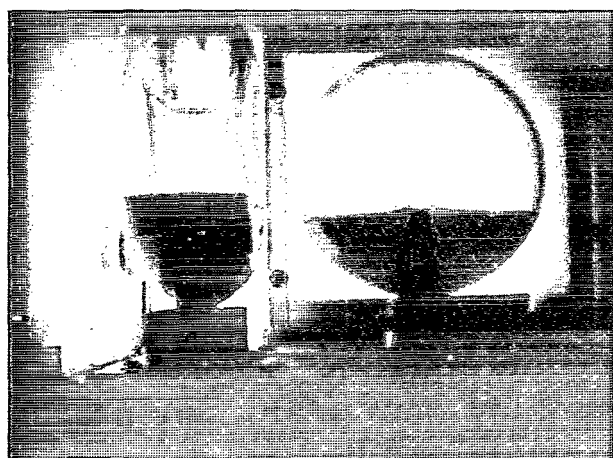
Zero-gravity configuration



(a) Tank mounting angle, 30° .



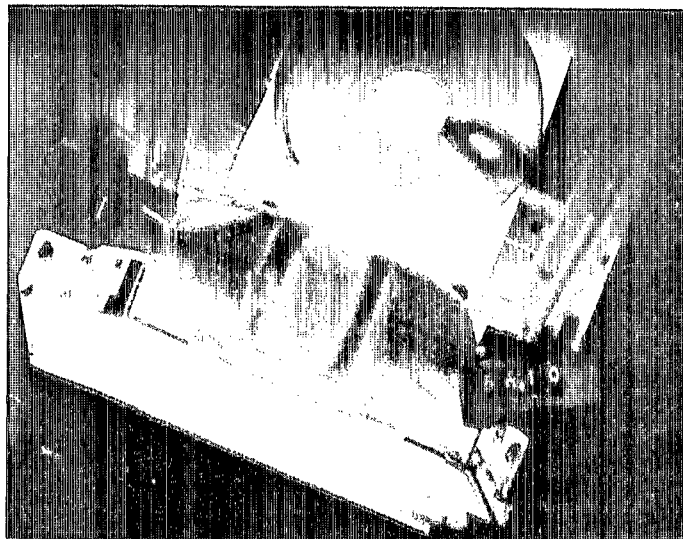
(b) Tank mounting angle, 60° .



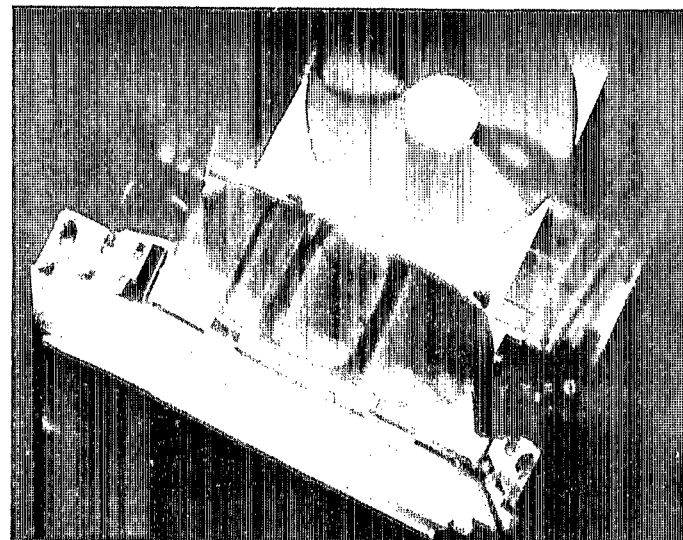
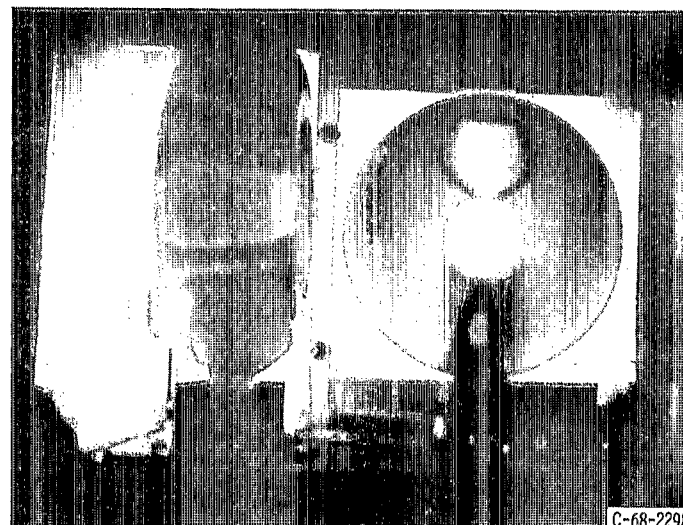
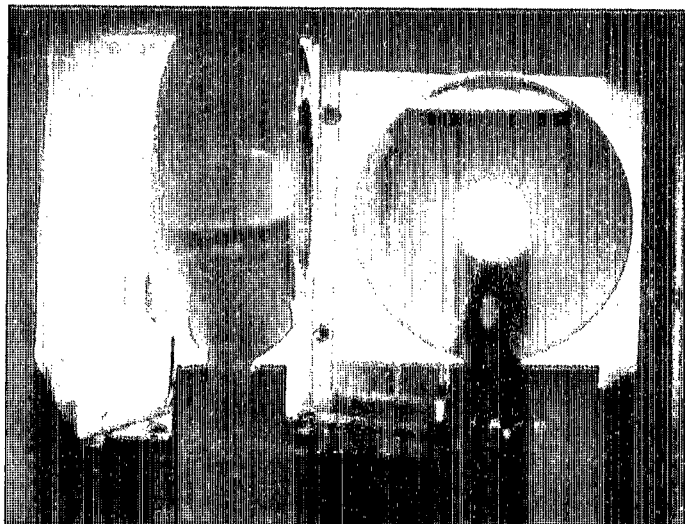
(c) Tank mounting angle, 90° .

Figure 13. - Configuration of liquid-vapor interface during weightlessness for moderate to high percentages of liquid volume (30 percent full). Predominant configuration for tank mounting angles greater than 0° . Major radius, 4 centimeters; minor radius, 2 centimeters.

Normal-gravity configuration



Zero-gravity configuration

(a) Tank mounting angle, 30° .

C-68-2298

(b) Tank mounting angle, 90° .

Figure 14. - Configuration of liquid-vapor interface during weightlessness for high percentage of liquid volume (90 percent full) and tank mounting angle greater than 0° . Major radius, 4 centimeters; minor radius, 2 centimeters.

creased toward 0° the region in which this configuration existed was narrowed. As can be seen from figure 11, above approximately 80 or 90 percent depending on the tank proportion, the vapor will assume the shape of a single spherical bubble, as it did in the case in which the tank mounting angle was 0° . This configuration is depicted in figure 14.

CONCLUDING REMARKS

The results of this experimental investigation indicate that there are three basic interface configurations for a liquid with a 0° static contact angle in a toroidal tank in a weightless environment. These configurations were dependent on the percentage of liquid volume and the tank mounting angle but were independent of tank size.

An interface configuration in which the liquid positioned itself on the tank wall farthest from the tank axis with the vapor positioning itself on the wall nearest the tank axis was observed for liquid volumes as large as 50 percent at a tank mounting angle of 0° . The effect of changing the tank mounting angle through 90° was to reduce the range over which a similar configuration occurred to liquid volumes as large as 20 or 30 percent. The small difference in limits from 20 to 30 percent reflects the effect of a change in tank proportions. A configuration in which the vapor took the shape of one or more spherical bubbles was observed at high percentages of liquid volume (above 80 or 90 percent). This was true at mounting angles from 0° to 90° , and the small difference in the percent limits may again be attributed to a change in tank proportions. A configuration in which the liquid tended to completely enclose one segment of the tank was observed for intermediate percentages of liquid volume; however, for tanks mounted at 0° , the available test time was insufficient to permit the interface to reach equilibrium.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 19, 1968,
124-09-03-01-22.

REFERENCES

1. Petrash, Donald A.; Nussle, Ralph C.; and Otto, Edward W.: Effect of Contact Angle and Tank Geometry on the Configuration of the Liquid-Vapor Interface During Weightlessness. NASA TN D-2075, 1963.

2. Petrash, Donald A.; Zappa, Robert F.; and Otto, Edward W.: Experimental Study of the Effects of Weightlessness on the Configuration of Mercury and Alcohol in Spherical Tanks. NASA TN D-1197, 1962.
3. Otto, Edward W.: Static and Dynamic Behavior of the Liquid-Vapor Interface During Weightlessness. AIChE Chem. Eng. Progr. Symp. Ser., vol. 62, no. 62, 1966, pp. 158-177.
4. Siegert, Clifford E.; Petrash, Donald A.; and Otto, Edward W.: Time Response of the Liquid-Vapor Interface After Entering Weightlessness. NASA TN D-2458, 1964.
5. McCarty, John Locke; Leonard, H. Wayne; and Walton, William C., Jr.: Experimental Investigation of the Natural Frequencies of Liquids in Toroidal Tanks. NASA TN D-531, 1960.
6. Sumner, Irving E.: Preliminary Experimental Investigation of Frequencies and Forces Resulting from Liquid Sloshing in Toroidal Tanks. NASA TN D-1709, 1963.

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

OSU 001 37 51 30S 68257 00903
AIR FORCE WEAPONS LABORATORY/AFWL/
KIRTLAND AIR FORCE BASE, NEW MEXICO 87117

ATTN: DR. ROYAL, ACTING CHIEF TECH. STAFF

POSTMASTER: If Undeliverable (Section 158
Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546